New Technologies for the Actuation and Control of Large Aperture Lightweight Optical Quality Mirrors

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[1]*Abstract*—There is a need for ever-larger apertures for use in space based optical imaging systems. The design of such mirrors involves a balance between (a) using lighter face sheet and lighter support structure, which reduces weight but increases the mirror surface deformations due to disturbances, and (b) using more dynamic actuated correction of the increased deformations, which increases weight due to the added actuators. Recent developments such as the ultra lightweight nanolaminate-based optical quality mirror face sheets (~0.2 kg/m^2 areal density) developed at Lawrence Livermore National Laboratories [2] are dramatically changing this balance in favor of more actuation and control. To realize the full potential of these new ultra lightweight optical quality face sheets, new ultra lightweight large stroke precision actuators need to be developed. This paper presents a set of candidate components: MEMS based large stroke (>100 microns) ultra lightweight (~0.01 gm) discrete inch worm actuator technology, and a distributed actuator technology, in the context of a novel lightweight active flexure-hinged substrate concept that uses the nanolaminate face sheet [1].

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1. INTRODUCTION

The science requirements of futuristic NASA missions indicate the need for very large aperture (>10m) class imaging space telescopes, to meet the light gathering and resolution requirements. The results of recent study programs have indicated that it is extremely difficult and expensive to fabricate lightweight glass-based mirrors with an areal density less than about 20 kg/m^2. Foam and SiC technologies have been under development, which may enable fabrication of mirrors with areal densities of about 10 kg/m^2, which is an improvement over glass, but still fall significantly short of the ultra lightweight potential of the nanolaminate. Membrane technology development has demonstrated that while the membrane itself is extremely lightweight, it requires a ring structure that is relatively very heavy, with the result the overall areal density is still in the range of about 10 kg/m^2.

The nanolaminate technology is a promising new mirror face sheet technology that is under development at Lawrence Livermore National Laboratories [2]. It provides an optical quality face sheet with near net shape, with surface roughness less than 10 Angstroms rms, with an areal density of only about 0.2 kg/m^2. It has other advantages such as low cost rapid replication process in its fabrication. It has significant in-plane stiffness, much higher than that of the membrane, making it possible to avoid the heavy ring support structure, but it is not stiff enough to avoid the support structure altogether. A novel flexure-hinged support structure was recently proposed [1] to provide a lightweight support structure to the nanolaminate face sheet, with the attractive property that the CTE mismatch between the face sheet and the support structure is accommodated by the active support truss structure, thereby greatly relaxing the thermal control requirements, which is important for large aperture mirrors. The practical realization of such a lightweight active support structure is predicated on the availability of ultra lightweight precision actuators with large stroke (~ tens of microns) and nanometer resolution. This novel support structure technology, while being considered here for the specific application to the nanolaminate mirror face sheets, is, in principle, applicable to any lightweight mirror face sheet.

The important point to be noted here is that while the mirror face sheet technologies have recently made significant advances to provide very lightweight (~0.2 kg/m^2) optical quality face sheets, available actuators are still relatively heavy and bulky. It is this actuator technology gap that is the focus of this paper: we need a paradigm shift from the current actuator state of the art which provides large force, small stroke (a few microns) precision heavy actuators, to the new generation which would provide large stroke (~ 50 microns) small force precision ultra lightweight actuators, to match the needs and properties of the new lightweight face sheets.

To put this in perspective, the new MEMS inchworm actuator discussed in this paper would be capable of a very large stroke of about 250 microns, with a resolution of a few nanometers, and occupies only about 2 mm^3, weighing only about 10 milligrams. Even if we use five hundred such actuators per square meter, the added weight is only about

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0.005 kg/m^2. To this, the weight of the drive electronics must also be added. A combination of addressable bus structure and microelectronics drive circuitry hybrid integrated with the MEMS actuator is proposed, to keep the weight of the drive electronics also at this very low level. With this bus structure, only four wires are needed, two for power and two for command/data. Thus, the ultra lightweight large stroke actuator technology proposed in this paper opens up a new design paradigm, and would enable truly ultra lightweight actuated mirrors for future generations of telescopes. More actuators also means increased processing complexity, but Moore's law continues to be valid, and so it may be anticipated that by the time these new technologies mature, adequate processing power will become available on board.

Using the proposed MEMS discrete actuator technology and the distributed actuator technology in the flexure-hinged truss substrate supporting the nanolaminate face sheet, the following is the rough estimate of the areal density, with a total of less than 1 kg/m^2 including drive electronics which will be on IC chips, and the wiring which will consist of a bus with four thin wires on a lightweight flexible plastic thin strip that can be conveniently routed on the beams of the truss structure.

Component	Estimate of Areal Density (kg/m^2)
Face Sheet (Nanolaminate, 0.1 mm thick)	0.2
MEMS Discrete Actuators, Drive Electronics on Chip	< 0.1
Distributed Actuators, Drive Electronics on Chip	< 0.2
Flexure Hinged Substrate	0.5
Total	< 1.0

More important than the ultra lightweight capability is the high tolerance of CTE mismatch that is made possible by the flexure hinged substrate concept and the large stroke of the actuators. This greatly reduces the temperature control requirements, which in turn reduces weight and complexity and also relaxes operational constraints. This is particularly important and enabling for very large aperture (10m class and larger) telescopes.

This paper discusses the components that go into this new concept, and how these components can go together, at a top level. The detailed analysis of the integrated performance of these components and their performance predictions at the telescope level are part of future research and development work. This work at present is at the concept and early laboratory experiment stages, and so the technology readiness level (TRL) is low, about 1 or 2. Future efforts will focus on the sensing and closed loop control, and on increasing the TRL, eventually to meet the needs of missions that are anticipated well into the future.

The conceptual design of a large travel MEMS inchworm actuator that is discussed in this paper has been under development in support of the proposed Advanced Segmented Silicon Space Telescope (ASSiST) [3]. The ASSiST concept exploits exciting capabilities offered by functional silicon optical segments. The issues studied under the ASSIST project included the development of large stroke (~250 microns) precision MEMS inchworm actuation for segment alignment. This inchworm device is well suited for application to the nanolaminate-hinged substrate deformable mirror concept that is discussed in this paper, because of its ultra light weight, large stroke, nanometer precision, and it consumes only microwatts to hold position.

While there is a wealth of literature on MEMS technology in general, few MEMS-based inchworm actuator developments have been reported in literature. A MEMS-based electrostatic linear inchworm motor has been reported [4]. This actuators move on the surface of a silicon wafer, thus cannot provide vertical motion. A mesoscale piezoelectric inchworm actuator has been developed [5]. The frictional clamping mechanism is responsible for the low force output associated with the bulky inchworm motor. A thermal inchworm actuation with thermo-elastic links has been published [6]. It shows a rough motion (5 μm step size) to generate with 50 μN @ 0.2 μm resolution. A proof-of-concept MEMS-based vertical inchworm actuator has been reported [7]. To our knowledge, none of these approaches provide large travel actuation (~ hundreds of microns) vertical actuation. Here, "vertical" refers to the surface of the MEMS structure, and not necessarily to the surface of the mirror. The proposed discrete MEMS actuators have a single degree of freedom, which can be geometrically oriented in any desired direction in the mirror substrate structure.

As mentioned earlier, by accommodating the tangential expansion of the face sheet, the hinged substrate concept [1] avoids the CTE mismatch problem, which is a major cause of figure errors. This also results in the corrective deformation required to being mainly in the surface-normal direction, which is well suited for the actuated hinged substrate, whose support flexures are normal to the mirror surface. However, if there are hoop stresses involved in the required deformation, these are best supported by tangential actuation. To provide tangential actuation, an active layer bonded to the backside of the nanolaminate face sheet is proposed. If the effect of hoop stresses is small, then the active layer can be omitted altogether. So the active layer is considered here as an option. The active layer, if included, must be capable of being commanded to match the tangential expansion of the face sheet, in addition to providing the tangential forces required to support hoop stresses. In plane actuators have been proposed by several researchers [9-12]. In this paper, a brief description of the development of the thin shell mirror structures laminated with segmented actuator patches is presented. The active layer adds less than 0.1 kg/m^2 to the areal density of the mirror.

First, the deformation requirements of the nanolaminate-hinged substrate mirror are presented, followed by the descriptions of the discrete MEMS inchworm actuator and the distributed actuator concepts.

2. The Actuator Requirements

A key enabler of the ultra lightweight mirror technology is the nanolaminate, which comes with optical quality polished near net shape, thereby eliminating costly and time consuming grinding and polishing steps. This allows the face sheet to be extremely thin, resulting in its ultra lightweight, about 0.2 kg/m^2 for a thickness of about 0.1mm. However, the nanolaminate is metallic, which means it has significant CTE (13E-6/Deg C). This introduces the problem of CTE mismatch between the face sheet and the supporting substrate, a problem whose solution in conventional designs requires very tight temperature control. This CTE mismatch problem is solved in the design proposed in this paper by using the novel flexure-hinged truss substrate, which can be commanded to expand or contract in the tangential direction also [1].

2.1 The Nano Laminate Face Sheet, and the Hinged Substrate

A sample of the nanolaminate face sheet material, fabricated by Dr. Troy Barbee of Lawrence Livermore National Laboratories, is shown in figure 1. It is made up of thousands of nanometer size layers of metallic material, alternating layers being made of two different carefully selected materials. A wide variety of metals can be used [2]. The net result is that the face sheet replicates the figure and polish of the mandrel on which it is grown, so that grinding, figuring and polishing steps are totally eliminated. The surface roughness is less than 10 angstroms rms. This allows the face sheet to remain extremely thin, only about 100 microns thick. In an actual mirror, the front surface can be a layer of gold, to provide high reflectivity. The replication process also lowers the cost per item, when produced in quantity.

Being extremely thin, the nanolaminate requires some form of support (substrate) to maintain its figure. Once a substrate is introduced, it becomes necessary to lightweight the substrate also, if we are to realize the ultra lightweight potential of the nano laminate. Also, the interface between the substrate and the face sheet introduces the problems of CTE mismatch, in the presence of operational temperature changes. As mentioned earlier, the flexure-hinged substrate allows tolerance of significant CTE mismatch.

The hinged substrate concept is illustrated in figure 2, showing how the face sheet is supported by a flexure hinged truss with a discrete ultra lightweight actuator in each actuated beam, and also, optionally, with an actuated active layer to provide tangential distributed actuation. The optional distributed layer is more effective when hoop stresses are involved in the deformation of the face sheet. The presence of any hoop stresses (which are largely avoided by the accommodation of CTE mismatch by the hinged substrate) depends on the type of deformation required to bring the mirror surface back into the ideal shape. The details of the theory behind the hinged truss structure can be found in [1].

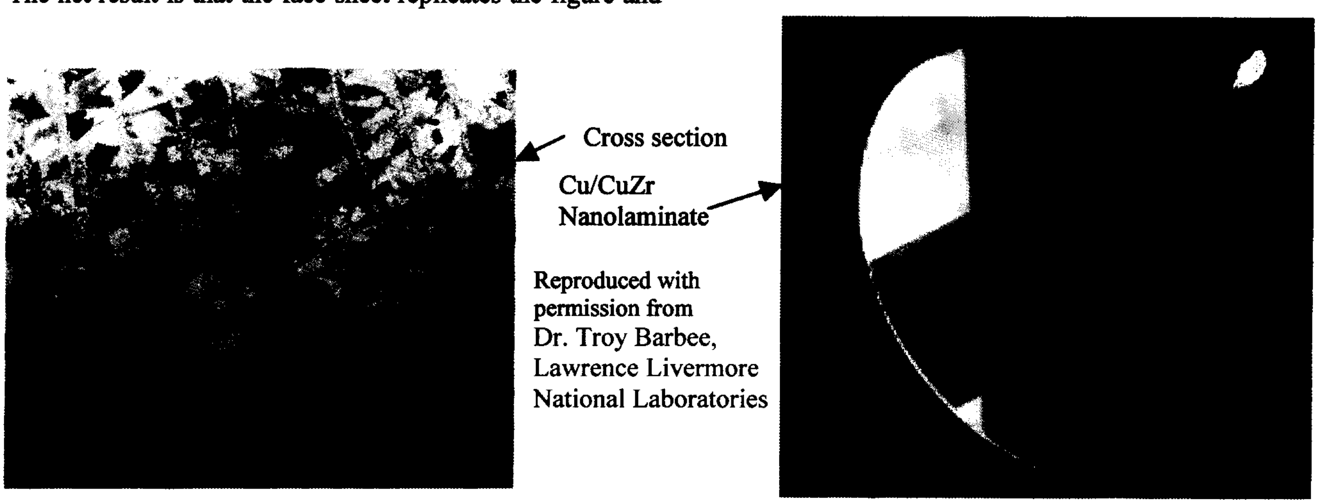


Figure 1 Ultra Lightweight Optical Quality Mirror Face Sheet produced by Nanolaminate Technology

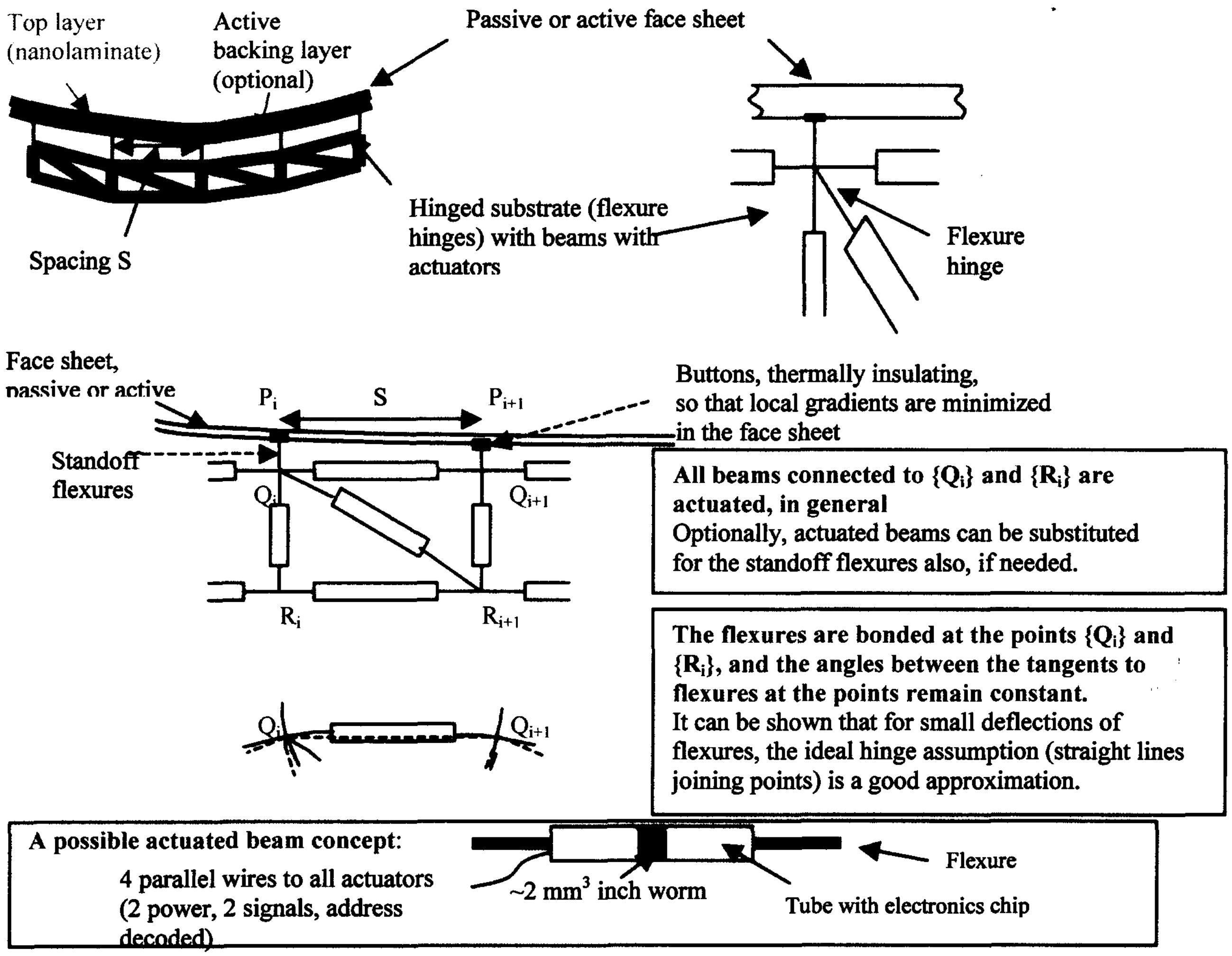


Figure 2 Novel Concept of Deformable Mirror with Flexure-Hinged Substrate

Points $\{P_i\}$ are the discrete support points under the face sheet, and points $\{Q_i\}$ and $\{R_i\}$ are the flexure hinge points in the truss structure. The deformations of the face sheet are small compared to the spacing S between the actuated support points. The hinges are actually "welded" joints of the flexures, avoiding the problems of micro slip and micro creep problems of sliding contact hinged joints. The "welded" joint of flexures means that the angles between the tangents to the flexures at the joint do not change, which means that the flexures may bend a little when the beams are actuated. For the very small angular changes involved, it can be shown that approximating the hinges with ideal hinges is valid. Under these conditions, the relationship between the discrete actuator motions and the motions of the hinge points of the substrate is linear, given by

$$H\, \underline{dxyz} = \underline{cmd} \qquad (1)$$

Where H is the (3n x 3n) matrix,
$\underline{dxyz} = \{ dx_i , dy_i , dz_i , i = 1 .. n \}^T$ = motions of the n hinge points in the truss in three (x,y,z) dof, $\underline{cmd}$ is the 3n column (command) vector whose first (3n-6) elements are the changes in the lengths of the (3n-6) beams, and the last six elements are the six rigid body motions, $\{dx0,dy0,dz0,d\theta x0,d\theta y0,d\theta z0\}^T$ of the entire structure. For a properly chosen geometry of the structure, the matrix H is invertible,

$$\underline{dxyz} = G\, \underline{cmd} \quad \text{where } G = H^{-1} \qquad (2)$$

Equations (1) and (2) are used to find the commands for the required displacements, and vice versa.
The truss structure is defined to be a statically determinate (minimally rigid) structure, that is, removing a beam will allow some hinge points to move relative to the others, and adding a beam would make it over-constrained. The details, including an algorithm to define such a minimally rigid hinged mirror support structure, are given in reference [1].
The minimally rigid hinged structure has the attractive property that unless acted upon by external forces, the stresses in the structure are always zero, regardless of any length changes in the beams such as due to thermal changes, or due to actuation. This minimizes the actuator force requirements.

If it is necessary to add additional beams to improve stiffness or to provide structural redundancy, then their lengths must be adjusted (by commanding the actuator in each such beam) to the values that will result in zero stress. The necessary relationships can be worked out in a manner similar to the above equations. Since the geometry is not perfectly known, there will still be some residual stresses, whenever the structure is thus over constrained.

The deformations normal to mirror surface are sensed using a suitable wave front sensor. The deformations tangential to mirror surface can be estimated from the temperature measurements, or metrology, or indirectly by its effects on the surface normal deformation. Knowing the deformation, equation (1) can be used to find the actuator commands needed to make the correction. Or, search techniques can be used, *knowing that a solution exists*. This correction can be done in a dynamic closed-loop fashion. The correctability of this actuation system depends on the geometry of the system and on the actuator resolution. By selecting sufficiently small actuator spacing, the correctability due to the geometry is improved to the required level. For the hinged substrate truss geometry, the geometrical amplification from the actuator (beam) axis to the mirror surface normal is typically less than 2. Therefore, for a typical budget of 10 nm rms mirror surface error, 5 nm resolution for the actuator would be adequate.

2.3 THE CTE MISMATCH TOLERANCE

In conventional mirror designs, the CTE mismatch between the face sheet and the substrate is a major cause of thermally induced deformations of the face sheet. In the case of the flexure hinged substrate, however, the face sheet deformation can be mostly decoupled from the substrate, because the actuated hinged substrate is capable of being commanded to change its shape in tangential as well as normal directions, and so it can be commanded to accommodate the tangential dimensional changes of the face sheet, thereby largely removing the CTE mismatch problem. If the discrete actuators in the beams of the hinged substrate are commanded so that the points $\{Q_i\}$ in the substrate (see figure 2) are moved in the tangential direction to line up behind the mirror surface points $\{P_i\}$, then there will be no bending moment in the standoff flexures, and in addition if they are moved in the normal direction to bring the surface points $\{P_i\}$ to the required figure of the mirror surface, then the required corrective deformation is mostly normal to the surface of the thin mirror face sheet. In doing this corrective deformation, tangential (hoop) stresses are minimized by *not* doing any focus correction (which is conveniently done by de-spacing the secondary mirror accordingly). There will still be some residual tangential stresses, and these will cause some uncorrectable surface normal deformations *in between support points*. If these are made sufficiently small to be tolerated (design variables include the spacing S and the face sheet stiffness), then there is no need for an active backing layer behind the mirror to provide the required tangential corrective forces.

If there is an active backing layer in the design, however, then it needs to be commanded to accommodate the tangential dimensional changes of the face sheet as well. If the active layer includes a thermal control mesh, then it is conceivable that by applying appropriate heat pattern, the thermal gradients in the face sheet may also be reduced. Because of the potential thermal mismatch problems between the nanolaminate face sheet and the active layer, the optional active layer is to be avoided if possible. It is included in the design space here for completeness.

When the thermal change in the face sheet is uniform (either due to external thermal load by itself, or through a combination of external thermal loads and internal (active layer) thermal control), with the substrate actuated to accommodate the tangential changes, the net result is be a uniform three dimensional size change in the entire mirror face sheet, which therefore results only in a shift in the prime focus, which can be readily accommodated by a corresponding despace of the secondary mirror. Therefore, we need to concern ourselves only with temperature gradients and their effects. Note that in contrast, in the conventional designs (with monolithic substrates), CTE mismatch would cause deformations even if the temperature change were uniform.

2.4 THE THERMAL DEFORMATIONS OF THE NANO LAMINATE FACE SHEET

For a 4m hexagonal aperture f/1.5 parabolic nano laminate mirror (with the material properties given below), a finite element model was used to predict the deformations for severe temperature profiles: uniform 10 Deg C bulk temperature change, and 1 Deg C/m gradient. These temperature profiles are at least an order of magnitude more severe than that used in conventional telescope designs.

The MSC/NASTRAN model of a 4 meter hexagonal center segment of an f/1.5 paraboloid nanolaminate face sheet supported by a flexure-hinged substrate is shown in figure 3. The parameters are:
Nanolaminate face sheet, modeled as a refined mesh with 37651 grid points:

Diameter (tip to tip)	4m
Thickness	100 microns
Modulus of Elasticity	95 GPa
Poisson's ratio	0.35
CTE	13E-6 /deg C
Thermal Conductivity	0.7 w/cm deg C

Substrate:

Number of beams	7554
Number of support points	1261
Number of points on back	1259
Spacing between support points	~ 10 cm
Beams diameter	1.16 mm
Flexure diameter	0.1mm
Modulus of elasticity	68.3 Gpa
Poisson's ratio	0.33

Note that the substrate is minimally rigid, that is,
number of beams = 3x number of points – 6.

The results of this structural analysis are shown in figures 4(a) and 4(b) for the thermal deformations of the face sheet alone. The purpose of this analysis is to find the magnitude of the stroke required, to a first order accuracy. As can be seen, the deformations are very large. Because several actuators (one in every beam in the truss structure, see figure 3) participate in the accommodation of the tangential deformation and in correcting the normal deformation, the stroke requirement of the actuator is not as large, but is still in the tens of microns range. The number of beam lengths per meter is a rough indicator of how many actuators may share the correction of the deformation gradient (deformation per meter), in a truss structure. Large highly local gradients are unlikely because of the high thermal conductivity of the nanolaminate. The number of beam lengths per meter also depends on whether or not distributed actuation (which is considered optional in this design) is used. If distributed actuation is used, then fewer (actuated) beam lengths per meter would suffice. Judging from the deformation profiles shown in figure 4, the deformation gradient is in the range of about 22 microns (Z only) to 140 microns (total) per meter. For a beam length of about 10 cm, there are about 10 beams per meter. All the beams will not share the total deformation uniformly. Assuming a factor of 3 to account for the spread in the participating actuators, we see that the actuator stroke requirement is in the range of about (140/10) x 3=42 microns. This is well within the goal of about 250 microns set for the development of the MEMS discrete actuator for the ASSiST project, and well above the capability of current state of the art solid-state discrete actuators. This analysis is conservative, because the CTE of the support structure has not been considered. In reality, it is the delta CTE that must be used, which will be smaller than the 13E-6/Deg C used here. The goal here is to come up with a design that can tolerate large CTE mismatch, with severe temperature profiles.

As explained earlier (Equation 2), the displacements of the actuators are linearly related to the deformations. Though this example is for a hexagonal central portion of a segmented primary, in general, the geometry can be tailored to any shape of the primary mirror face sheet.

The NASTRAN model, including the substrate, was then exercised to find the influence function of a single actuator, that is, the response of the face sheet to the actuation of a single actuator. The results are shown in figure 4(c) for an actuator on the backside, and in figure 4(d) for an actuator in the back-to-front beam of the substrate. The plots are for the surface changes in the direction of the optical axis, which is the main component that affects the wave front error. These influence function plots show that (a) the flexure-hinged substrate works, and (b) the actuator influence function is not localized.

To correct a given surface profile error of the face sheet (in both surface normal and tangential directions), the approach is to first determine the best-fit geometrical shape that has the correct figure. This would be the shape to which the mirror has to be corrected. From this we can determine the locations to which the points on the front side of the substrate (points $\{Q_i\}$ in figure 2) should be moved to, in order to effect this correction. Then, using equation (1), the required actuator commands are found. Note that this is a forward problem, not the inverse problem, that is, no matrix inversion is required. Also, note that in applying equation (1) the positions of the back-side points of the substrate (points $\{R_i\}$ in figure 2) are arbitrary, and so they can be either left unchanged, or used constructively, such as to minimize the bending moments in the standoff flexures.

The ability to actuate the substrate to match the tangential dimensional changes of the face sheet provides the ability to tolerate the CTE mismatch. But to do this we need the knowledge of the dimensional changes of the face sheet and the substrate. This challenge can be met through metrology, temperature sensing and thermal models, and from the quilting effects of the face sheet itself that will be evident in suitable wave front sensor measurements. The sensing, processing and closed-loop control aspects of this problem form the subject matter of on-going and future research work in this area. This paper addresses mainly the component requirements of the actuation part of the system.

3. LARGE DYNAMIC RANGE VERTICAL TRAVEL INCHWORM MICROACTUATOR

We propose here a novel MEMS-based piezoelectric inchworm micro-actuator capable of large vertical travel (~ hundred microns) with precision step motion as shown in figure 5. Our inchworm technology is achieved by combining piezoelectric-driving and electrostatic-clamping actuations within silicon microstructures.The novel features of the actuator concept are:

1) Optimized electrode gap using bi-stable flexure beams
2) Large actuation travel enabled by polymeric materials

3.1 *FABRICATION PROCESS (REACTIVE ION ETCHING PROCESS)*

Our initial efforts have focused on performing Deep Reactive Ion Etching (DRIE) experiments for the microfabrication of the MEMS inchworm actuators. Further development of a robust DRIE process is needed for obtaining smooth, vertical sidewalls required for nanometer step resolution for the inchworm actuation.

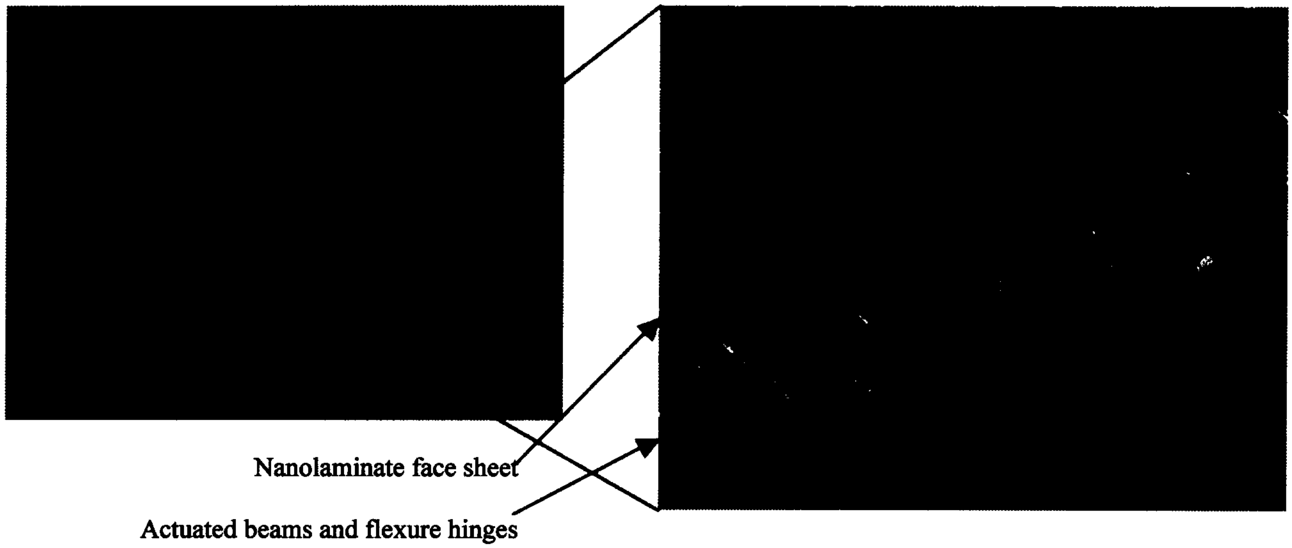
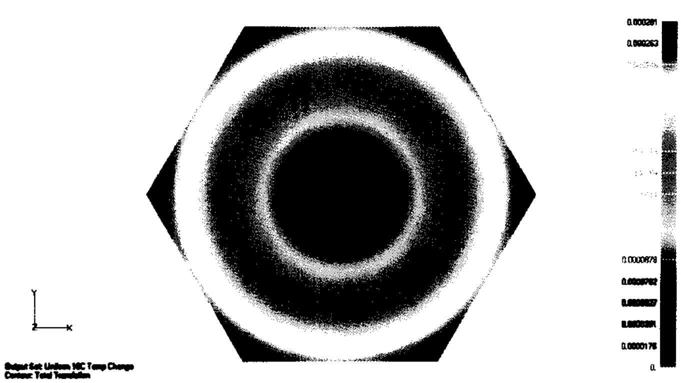
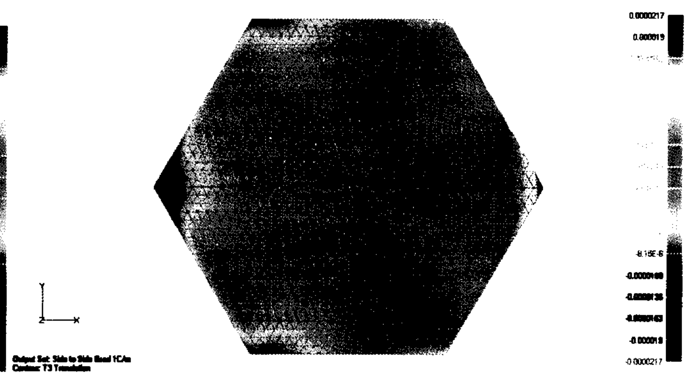


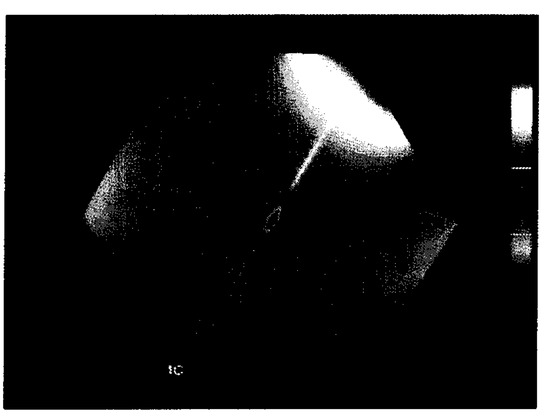
Figure 3. Four meter hexagonal paraboloid nanolaminate face sheet supported by hinged substrate



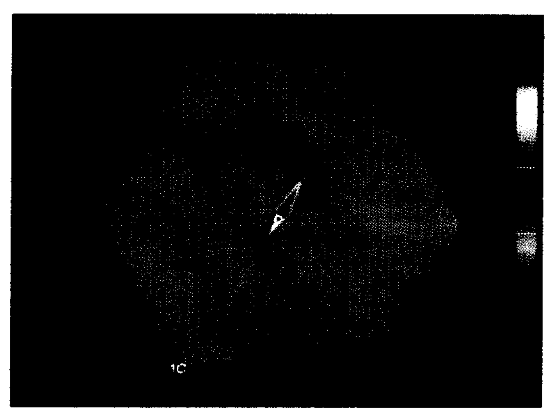
(a) 10 Deg C Uniform Change, Total: Max = 281 um
Total Deformation Gradient ~ 140 um/m
(face sheet alone modeled)



(b) 1 Deg C/m Side-to-Side Gradient, Z: Max = 43 um
Z axis Deformation Gradient ~ 22 um/m
(face sheet alone modeled)



(c) Influence function of actuator in a backside beam
Peak response / actuator motion = ~1.0
(face sheet and substrate modeled)



(d) Influence function of actuator in back-to-front beam
Peak response / actuator motion = ~1.0
(face sheet and substrate modeled)

Figure 4. Deformations of 4m f/1.5 Paraboloid Nanolaminate Mirror (0.1mm thickness)

3.2 Design of the Mechanical Structure

An inchworm actuator device consists of a piezoelectric stack actuator bonded to a silicon driver, a pair of holders, a slider, and a pair of polymer beams connected with a centrally clamped flexure beam. All the parts except for the piezoelectric stack and the polymer beams are made from a 350-micron-thick silicon-on-insulator (SOI) wafer. The estimated clamping force is 1 N. Since the step motion size (step resolution) is critically dependent on the smoothness and straightness of the sidewalls, a robust fabrication process for smooth, vertical sidewalls needs to be developed.

The inchworm actuator motion depends on the sequential activation of actuation elements. It is essentially a linear motor with extremely fine resolution. The ultimate goal of this research is to develop inchworm microactuator systems capable of simultaneously providing nanometer resolution, large output force, large travel range, and compactness for ultra precision positioning. The minimum width of trenches etched in silicon via the DRIE process is determined primarily by the achievable aspect ratio of the etching process, which is typically 25:1. Thus, trench widths on the order of 15~25 microns, are obtained for silicon microstructures fabricated from 350~500-micron-thick wafers. The use of such wide trenches for electrostatic clamping could result in defective actuation with attendant high voltage operation. Therefore, a centrally clamped, bi-stable flexure beam is incorporated in the design in order to reduce the gap between the slider and the driver/holder. The flexure beam connected to the slider is designed to snap towards the driver, via a mechanical buckling process, and thereby reduce the initial gap (for the electrostatic actuation) between the slider and driver/holder. A considerable amount of work remains to be done in order to optimize the design and fabrication process for this type of flexure beam structure. Estimates of total travel greater than 250 μm have been obtained for polymeric materials such as Teflon, Parylene and Silicone rubber (low Young's moduli) when used for the compliant beam structures.

3.3 *Actuation Mechanism*

The inchworm actuation mechanism works as follows:

1) The centrally clamped flexure beam is made to snap down to the 2nd stable position by means of an external probe. The snap down process makes the T-bar push the slider toward the driver. The polymeric beam is compliant enough to accommodate the shear strain required for this action. The snap down insures that the gap between the slider and the driver is within a couple of microns.
2) The slider is then electrostatically clamped to the driver. The driver is subsequently pushed upward by the piezoelectric stack actuator directly bonded to the driver. The slider also moves upward with the driver.
3) The slider is then electrostatically clamped by the fixed holders. Next, the slider is released from the driver. The released driver moves downward via piezoelectric actuation, while the slider remains clamped to the fixed holders.
4) Vertical inchworm actuation is achieved by repeating these steps (step 2-3).

Note that the flexure beam snaps down only once, in step 1, and not during every cycle of actuation. The ultimate device is expected to have the following specifications:

- Operation up to 1 kHz
- Operation at temperatures at or below 77K with 15-20% room temperature efficiency
- 250 μm total travel with nanometer-level precision
- Electrostatic holding force between segments of approximately 1 N (@ 100V)
- Mean steady-state power consumption ≤100 mW per actuator, during actuation.

Space qualification of this silicon based inchworm actuator technology should not present any problems.

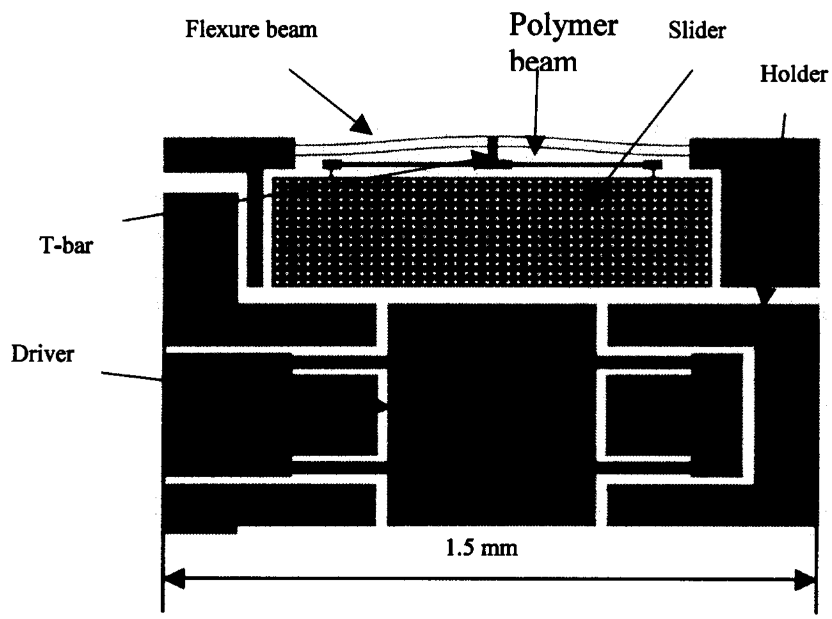


Figure 5 Top view of the actuator layout (motion is in-out of plane of diagram)

4. THE DISTRIBUTED ACTUATOR

Distributed piezoelectric actuator patches bonded on structures can be used for active precision shape control of the thin nanolaminate face sheet for figure control within the span S (see figure 2) of the spacing of support points of the flexure-hinged substrate, if required, as an option. The desired deformation field in the structure is obtained through the application of localized actuation forces and moments generated by expanding or contracting bonded piezoelectric distributed actuators. A newly developed formulation and numerical example to predict the response of shallow spherical aperture subjected to excitation from surface-bonded induced strain actuators were carried out in the research. This will be presented in brief. A full description of the mechanical modeling is being published in Reference [13]. The modeling of a piezoelectric actuated thin shell requires the modeling of first the electrical response of the piezoelectric film. This then needs to be integrated and solved with the nonlinear mechanics of the thin shell. The general constitutive equations of piezoelectric material were developed [14], and simplified using the thin shell assumption [13]. A nonlinear model for shell structures excited harmonically with induced strain actuator surface bonded patches was developed following the approach of Tzou *et al* [12]. Assume there is a distributed actuator layer laminated on the surface of the spherical shell and that the actuator layer is bi-axially sensitive material. As shown in figure 6, the distributed actuator patch is defined by the coordinates ϕ_1^*, ϕ_2^* in the meridional direction and ψ_1^*, ψ_2^* in the circumferential direction. Other geometries, such as the paraboloid and the support spacing geometry of the hinged substrate shown in figure 2, can be treated in a similar fashion.

Examples of Distributed Actuators

The piezoelectric patches bonded to the back surface of the face sheet consist of sectors or separate strips with control electrodes. To verify the validity of the modeling, a sample 10 cm mirror system is made as shown in figure 7, where a thin shell structure is patched with eight sectors of PVDF sector-like actuators to form an adaptive system. Etched electrodes are prepared (left), then assembled with the support fixtures (middle), to form the mirror system for testing (right). Note that the support fixtures are only for testing purposes. When the actuator layer is integrated on the back of the mirror face sheet, the support structure will be only the substrate structure. In figures 8 are two examples of the calculation results of the contour plots of the mirror actuated with a voltage of +100 volt. The left hand side is the actuated actuator patch, the right hand side is the calculated response of the normal displacement of the surface.

Through the development of this research, the fundamental distributed local and global actuation and control of mirror structures can be achieved. However, through the investigation, it was found that the some deformation of the surface like tilt or shear could not be easily fixed through the uniform pad actuators. Thus, in this invention, a new design is proposed. It is composed of four strip-like actuators with off-axis arrangement to perform bending and twisting forces for a special adjustment of localized aberration. By using the innovative off-axis actuator design with the bending/twisting function, the patched unit cell actuator can eliminate the total surface area of the actuators for regular patched or normal actuators. The aerial density of the adaptive optics can thus be reduced.

Space qualification of the PVDF material is an issue that must be addressed to qualify the proposed distributed actuator technology for space missions.

5. Conclusions and Future Work

New ultra lightweight actuator components, commensurate with the new nanolaminate ultra lightweight mirror face sheet technology, have been presented in the context of the novel flexure-hinged substrate, to provide the basis for the conceptual design of an ultra lightweight (~ 1 kg/m^2) large aperture deformable mirror that is tolerant of large CTE mismatch, and temperature profiles that are severe compared to current state of the art designs. Future efforts will include integrated analysis and performance prediction of this promising new mirror concept in severe thermal environments.

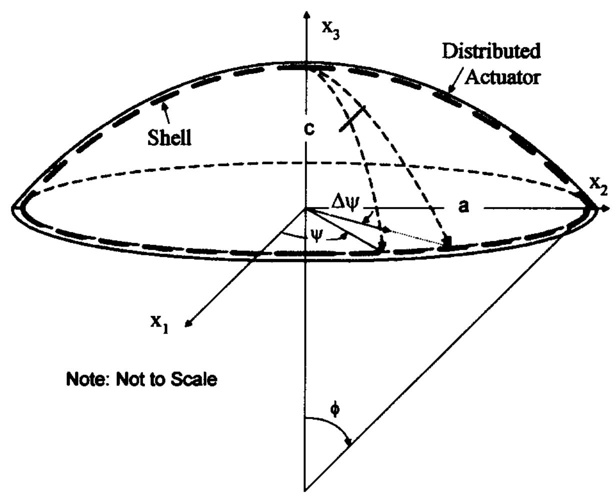


Figure 6: A thin hemispherical shell with a distributed patch actuator.

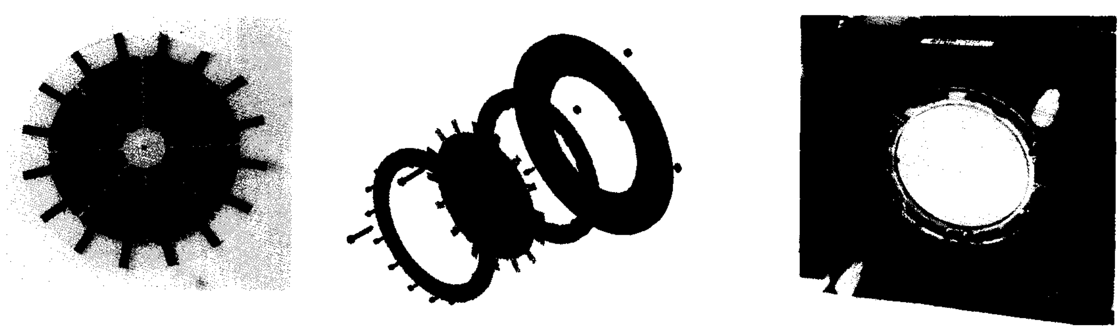
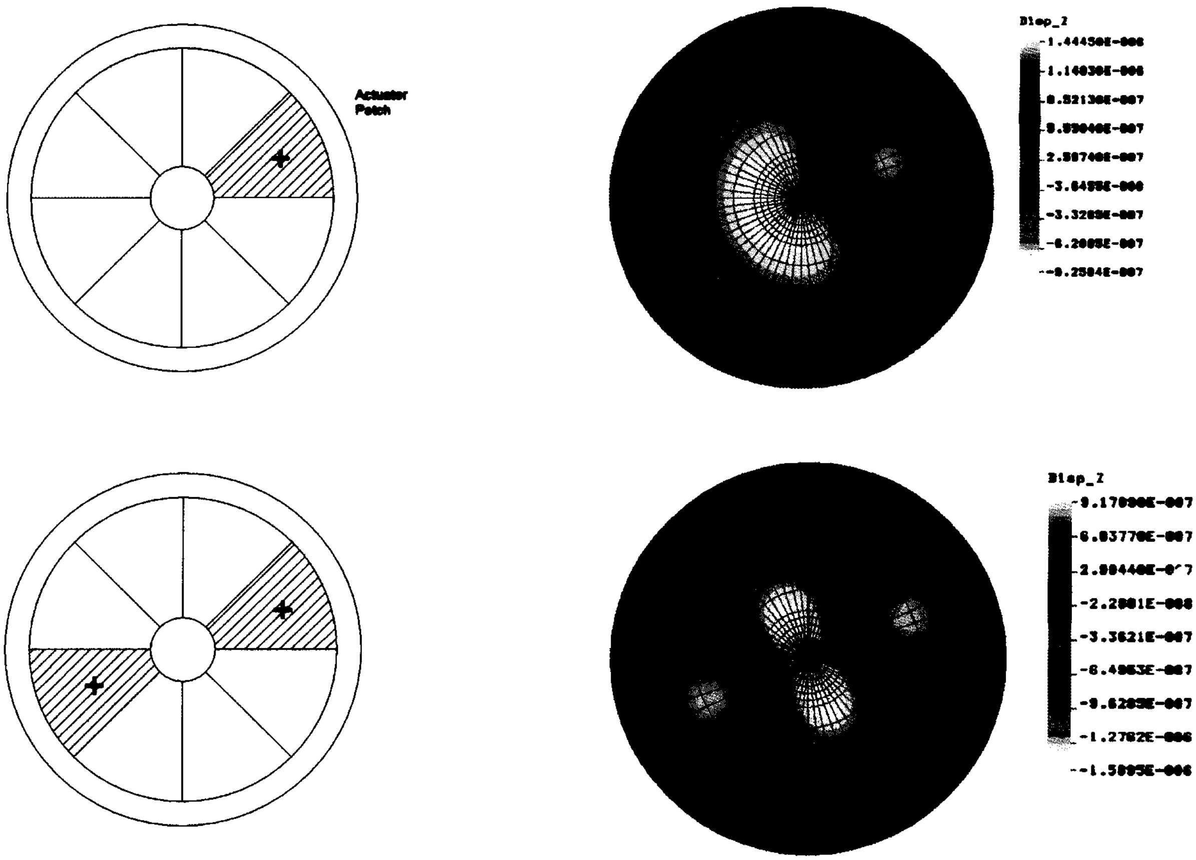


Figure 7 A PVDF Mirror System in a Test Fixture



.Figure 8 Model Predictions of PVDF Distributed Actuation

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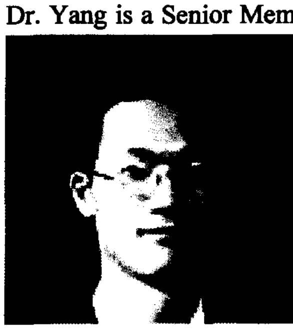

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